Discovering New Light States with Neutrino Experiments

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work with R. Essig, J. Kaplan, N. Toro

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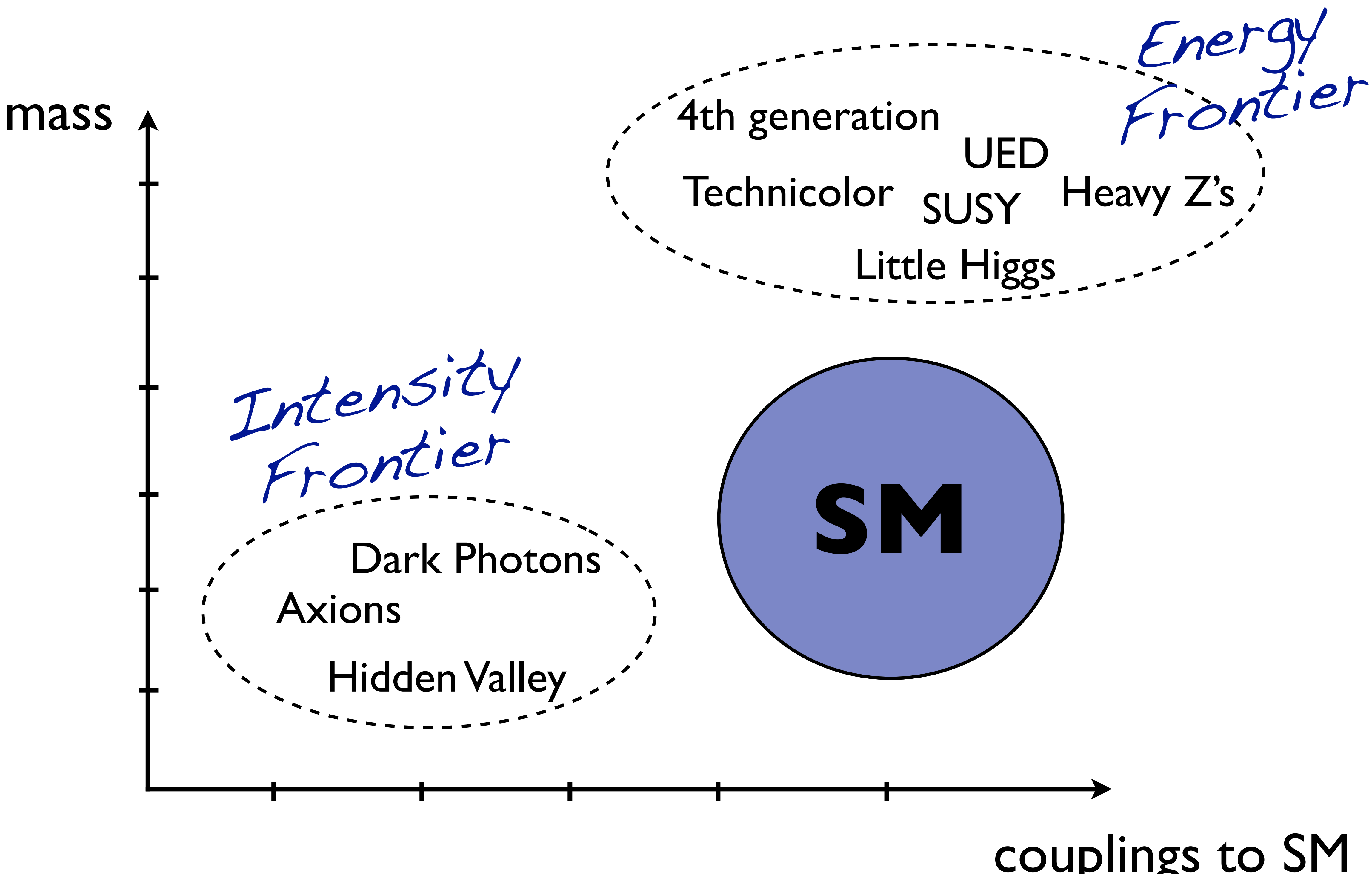
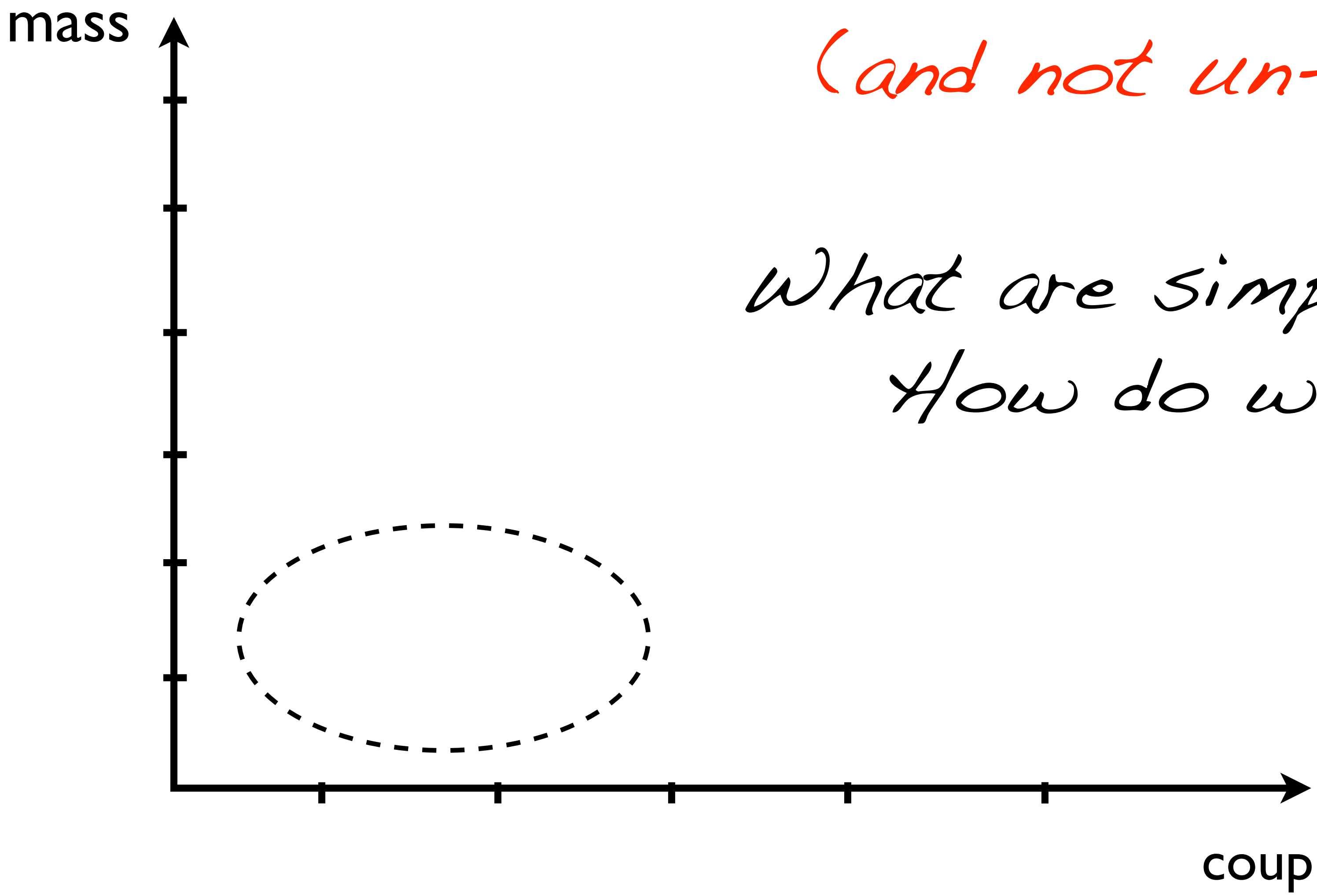
Where is New Physics?



In this talk I would like to advertise:
Neutrino experiments can look there
already with existing data.

why should we look?
because we can. models are simple.
(and not un-motivated)

What are simple models to probe?
How do we look for them?



Outline

- **Models**
  - Axions
  - Dark photons
- **Axion** limits from **neutrino experiments**:
  - from **protons** hitting target.
  - from **muons** hitting rock.
- Axion reach for μ **fixed-target** experiments.
- Conclusions and thoughts.

Models

Axions

* A pseudo-Nambu-Goldsotne boson (PNGB) is naturally light. Couples to matter with derivatives.
* Using e.o.m. one gets:

$$\mathcal{L}_a = \frac{m_\psi}{F} a\bar{\psi}\gamma_5\psi$$

* Note: PNGBs couple to mass (more later).
* Arise as R-axions, axions, in the NMSSM, etc.

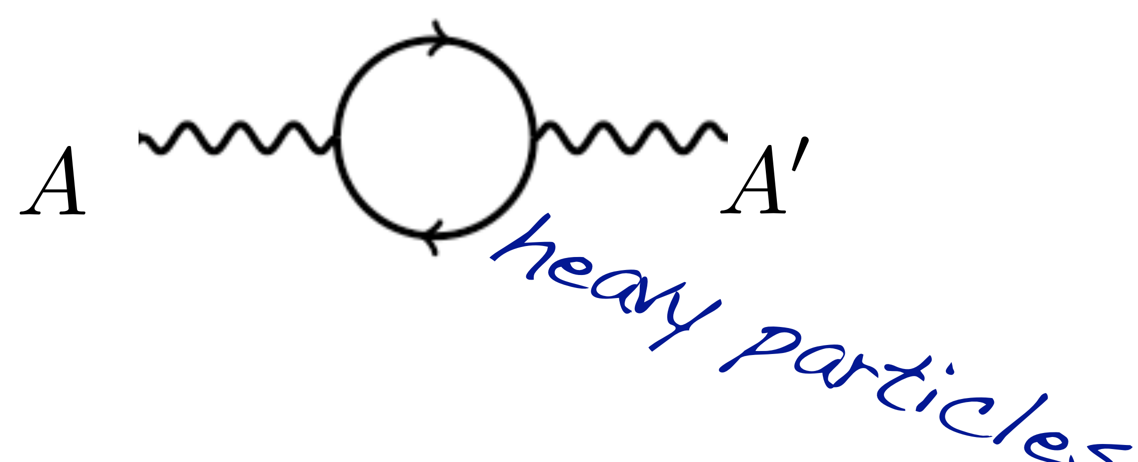
Dark Photons

* Consider a dark sector that has a "photon" with a mas of MeV - GeV.

* We can write a kinetic mixing

$$\delta\mathcal{L} = \frac{\epsilon_Y}{2} F'_{\mu\nu} F^{\mu\nu}_Y \quad \Rightarrow \quad \delta\mathcal{L} = \epsilon e A'_\mu \bar{\psi}\gamma^\mu\psi$$

* The mixing parameter, ϵ , can be naturally small.

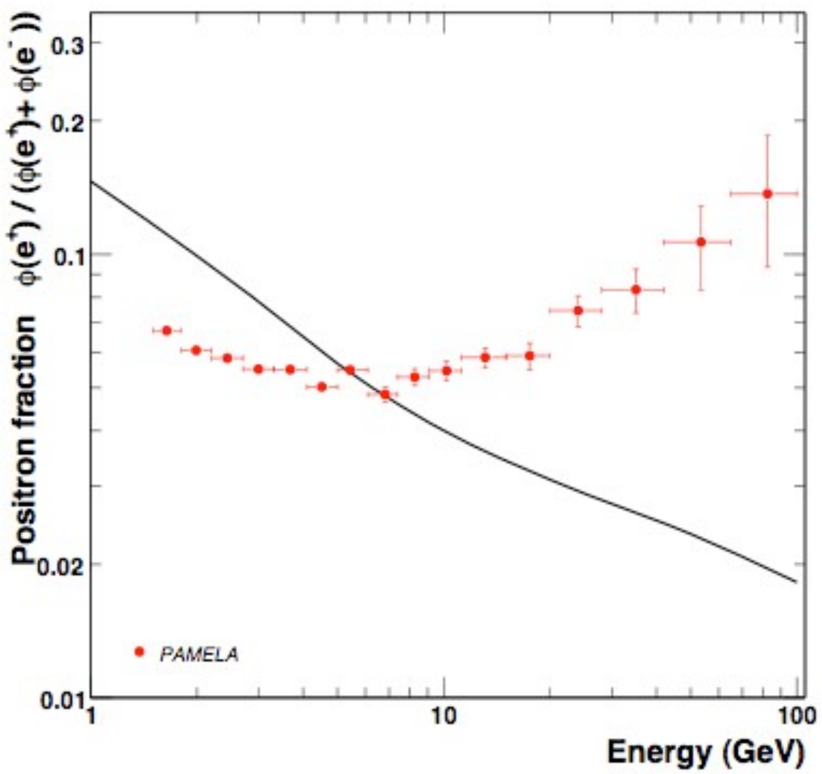


etc...

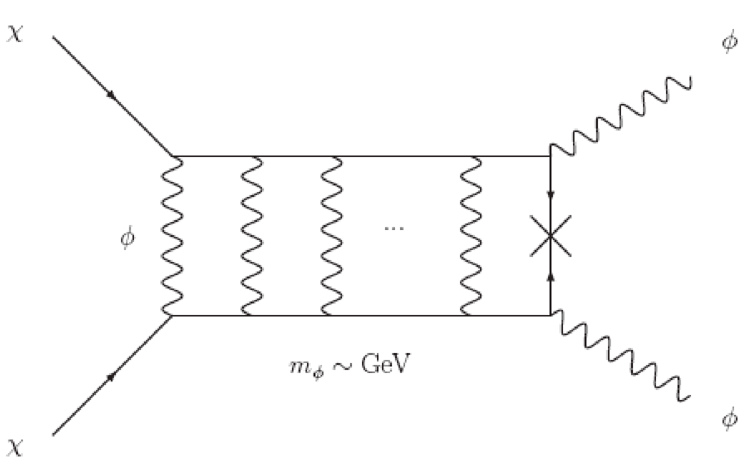
* There are many more possibilities:
  - Dark photon + dark higgs
  - Hidden valley models.
  - Light B-L gauge.
  - $L_\mu - L_\tau$ gauge bosons.
  - ....

Hints of light states?

* PAMELA provided a “hint” of dark matter annihilation with:
  - a rate that’s too high.
  - Annihilation only to leptons.



* A new light state coupling to dark matter helps with both:
  - Sommerfed enhancement.
  - Annihilation to light state, goes to leptons if its below a couple of GeV.



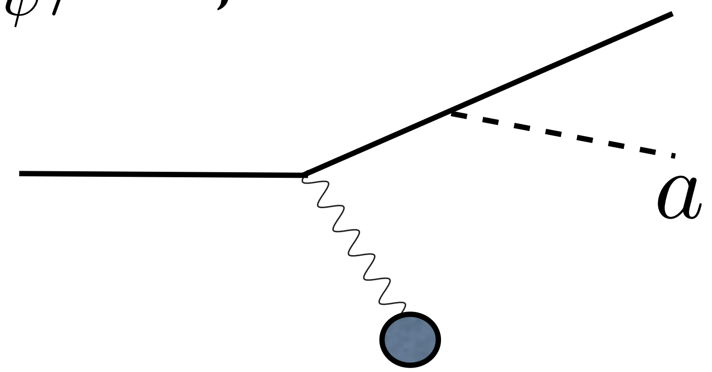
see Joachim's talk for MINOS
motivation for light states.

Limits on Axions

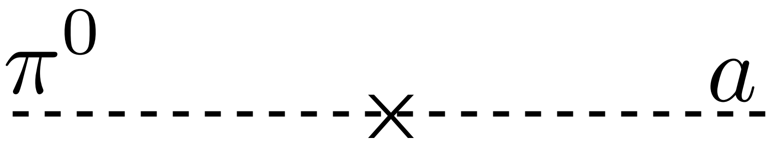
(a.k.a. PNGB's)

Axion - Production

* **“a-sstrahlung”:**
rule of thumb - for every bremsstrahlung photon there is a small probability, m_ψ^2/F^2 , to emit an axion instead.

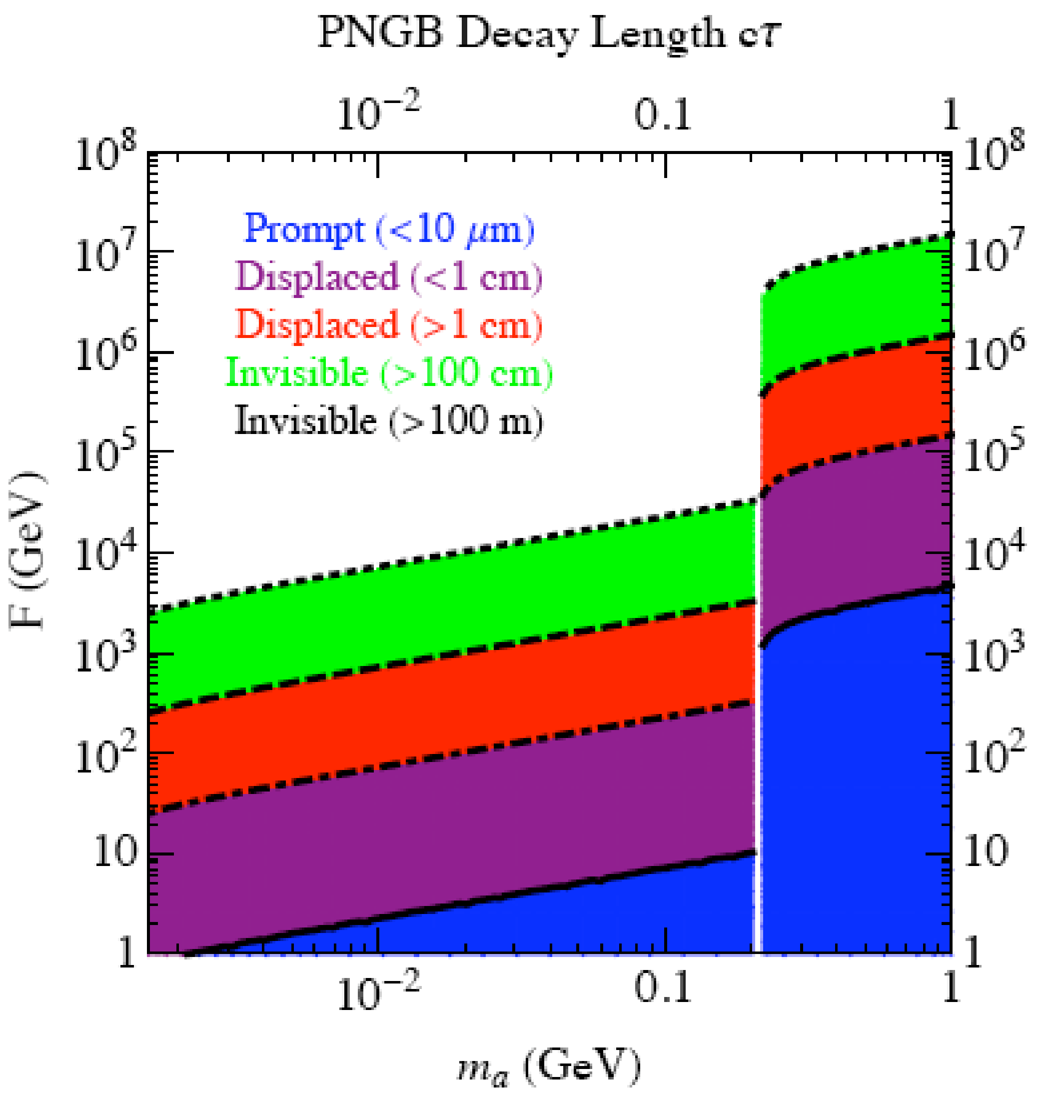


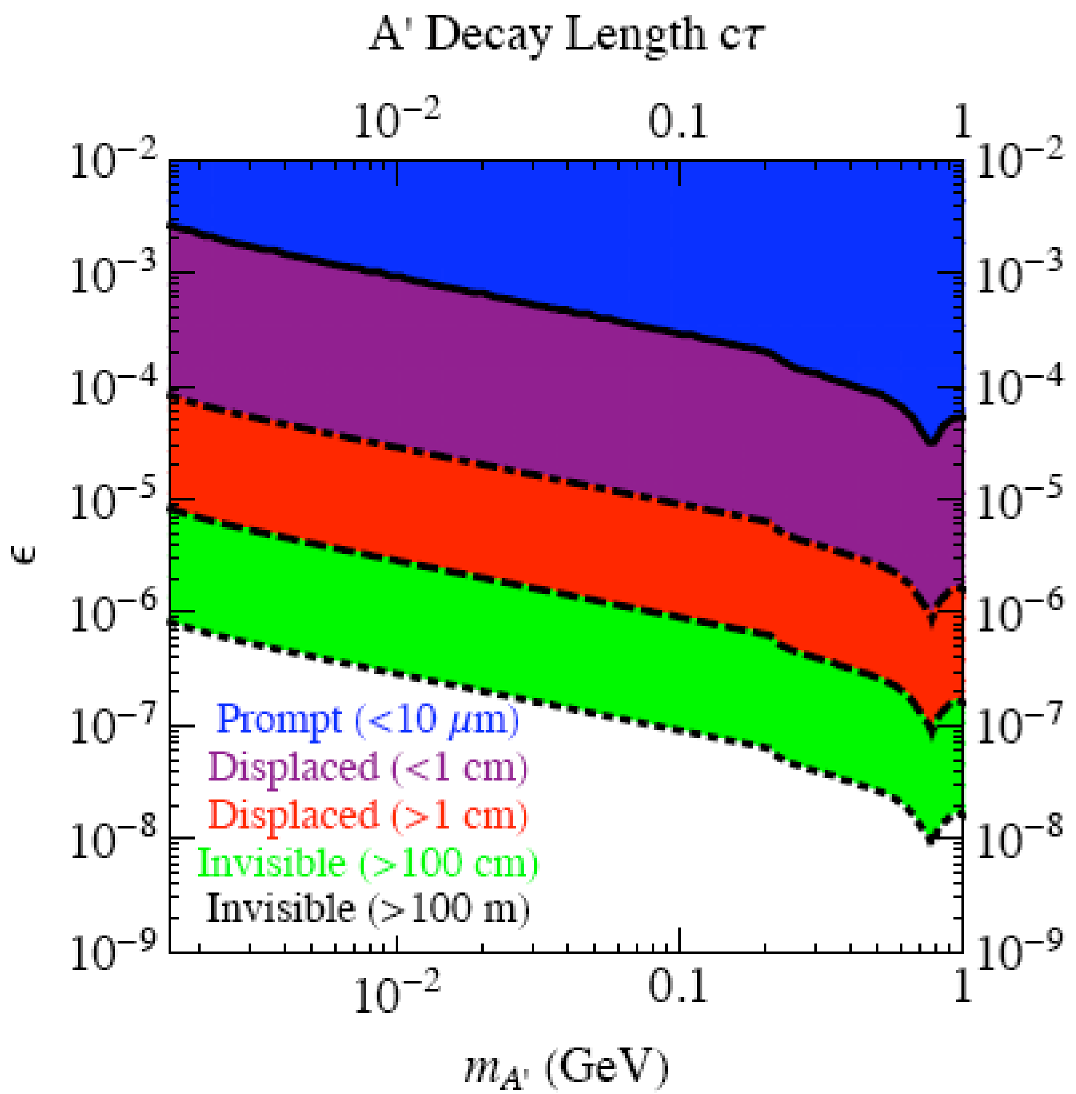
* **Mixing with a pion:**
Every produced pion can be an axion instead, with a some small probability $\sim f_\pi^2/F^2$.



Decay

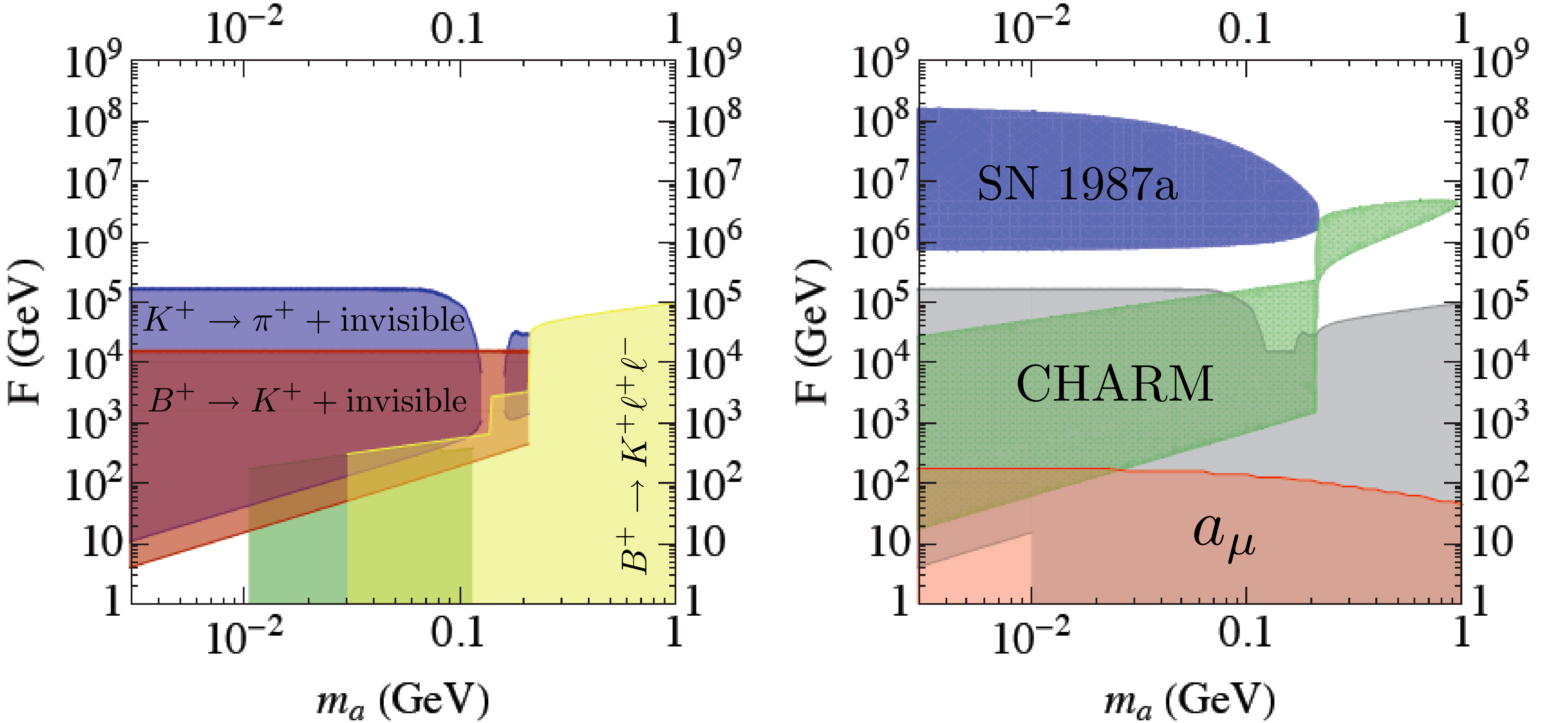
* Decay lengths can be either long (>100m) or short (prompt).





Axion - existing limits

* Limits on axions come from flavor, g-2, SN 1987a, and from CHARM (beam dump at CERN).

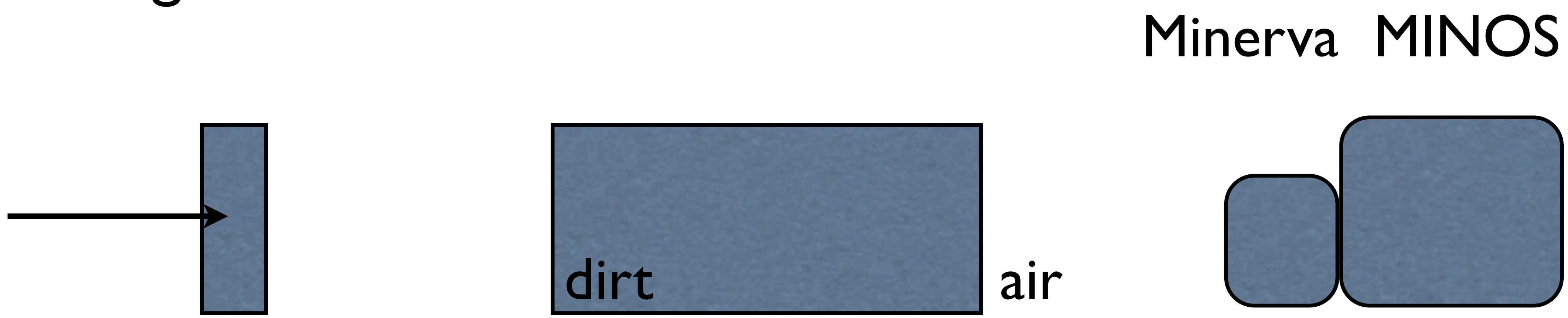


Note: g-2 is negative.

But could turn positive at 2-loops if it couples to tau.

-Beams as Beam Dumps

* Every neutrino beam starts with protons striking a target:



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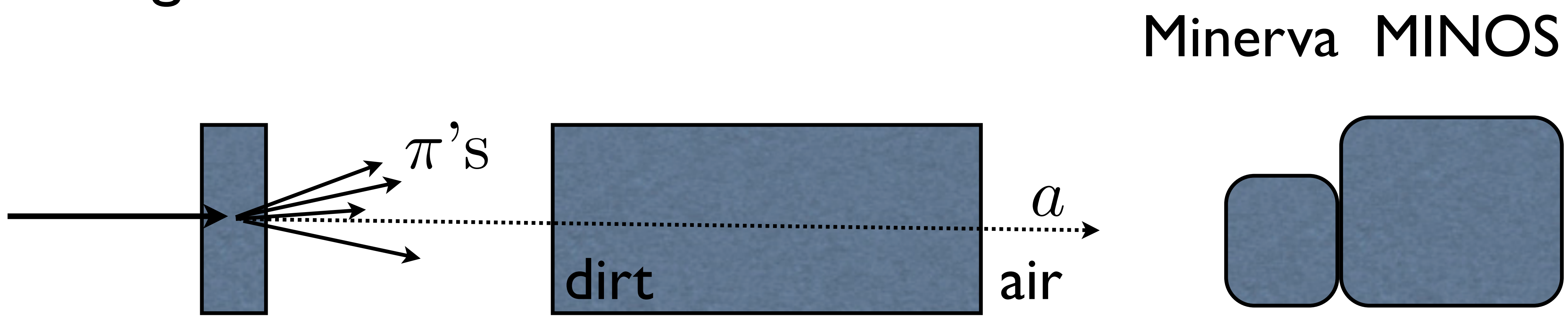

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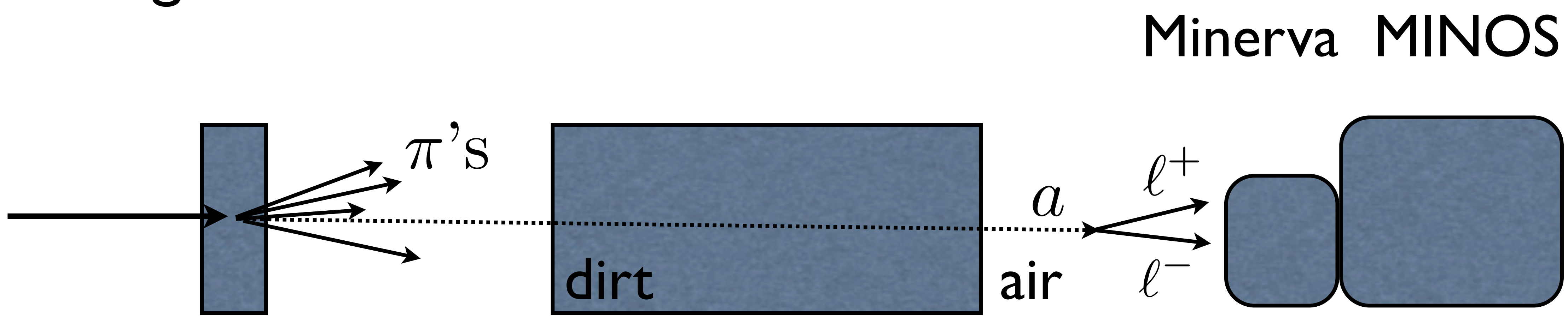

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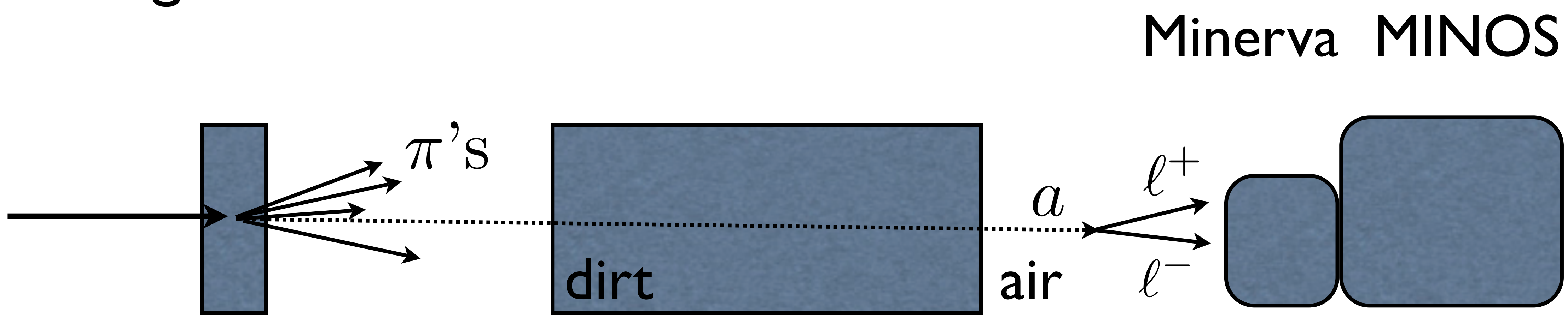


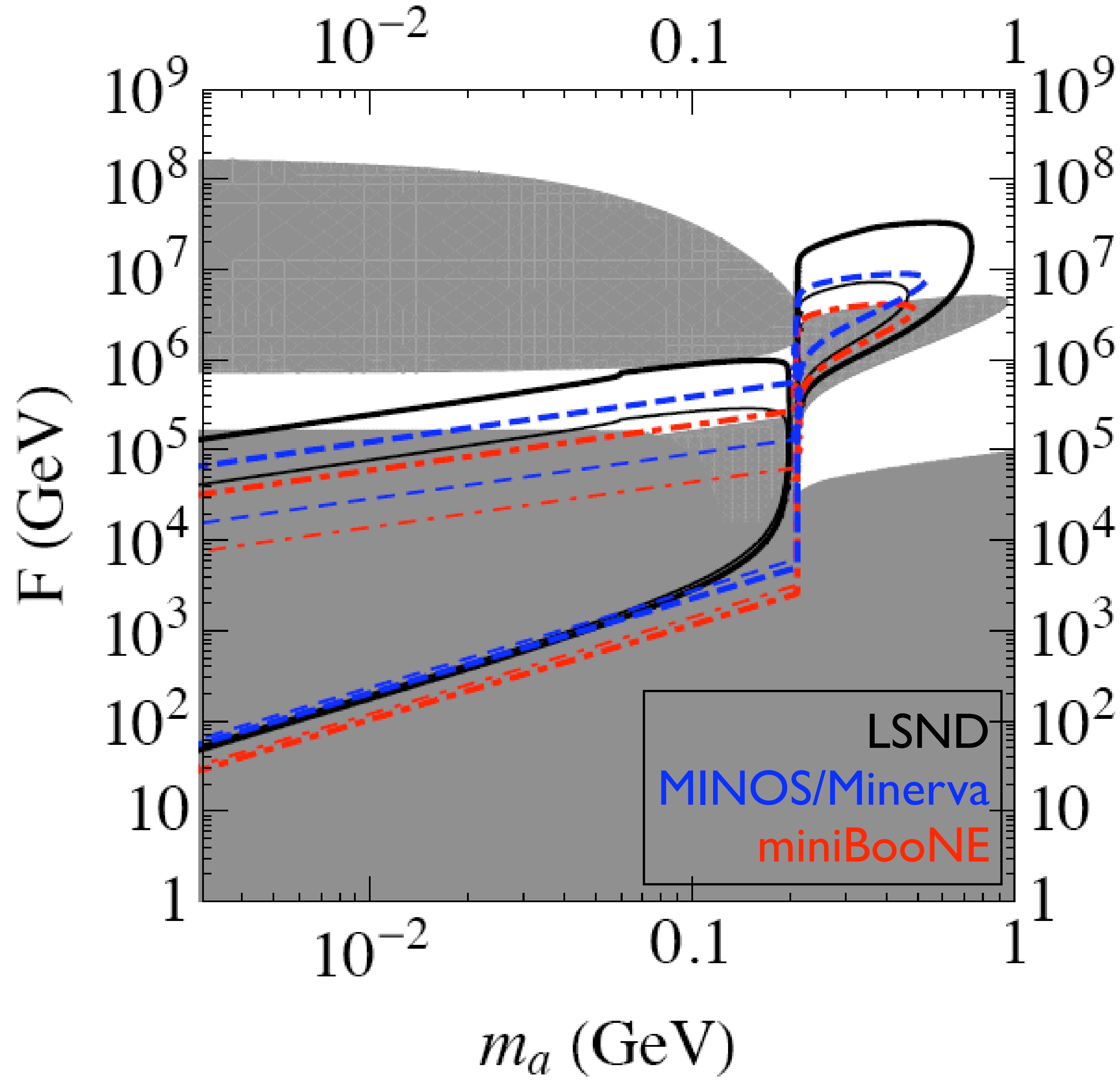
<u>Signal</u>:

- **lepton (or photon) pair originating from a single point in air.**
- **Reconstruct a mass peak.**

MINOS & Minerva are complementary!

Limits

- Gap b/w CHARM and SN partially closes.
- LSND dominates thanks to number of protons on target.
- Future facilities can close the gap?



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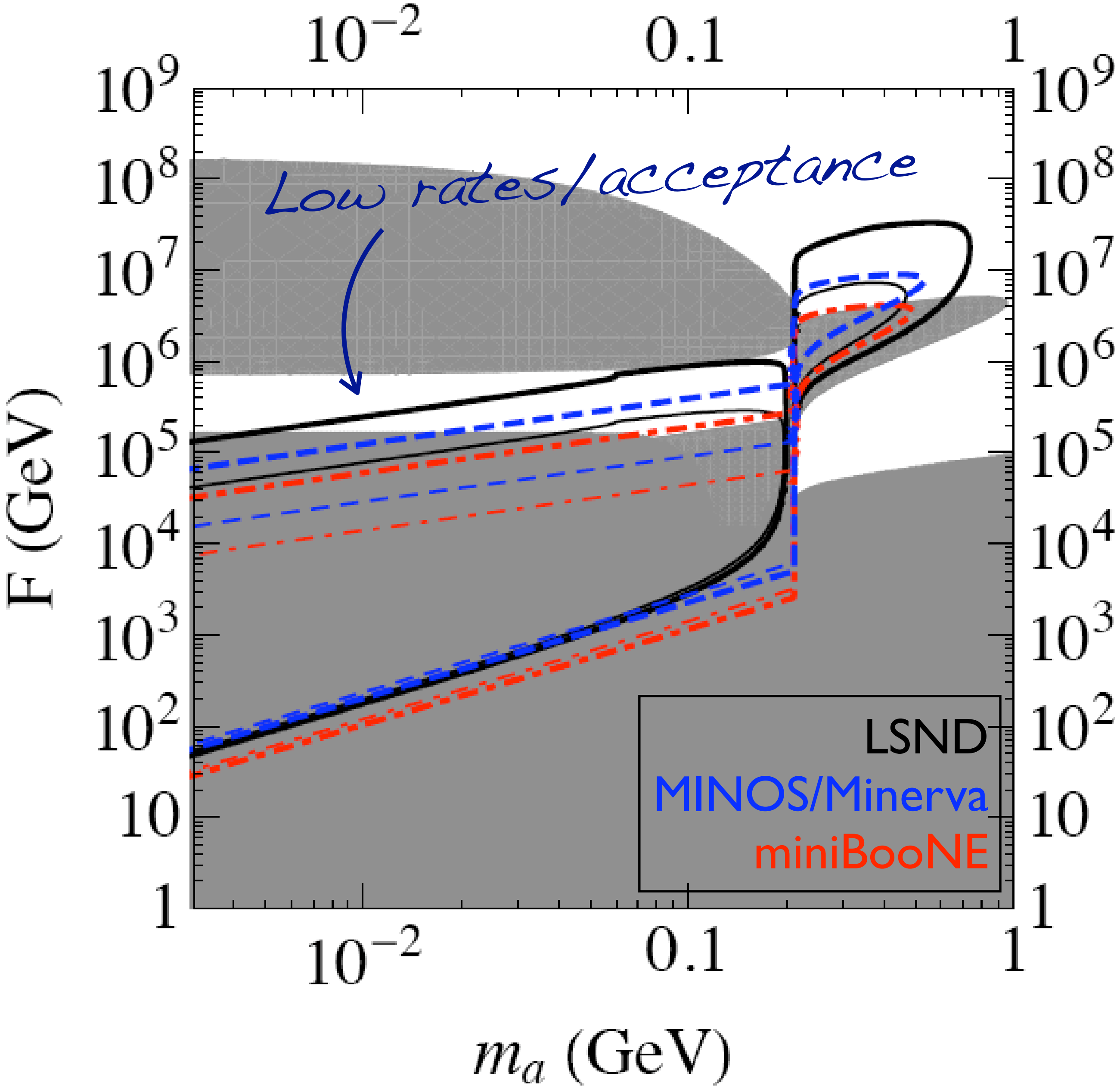

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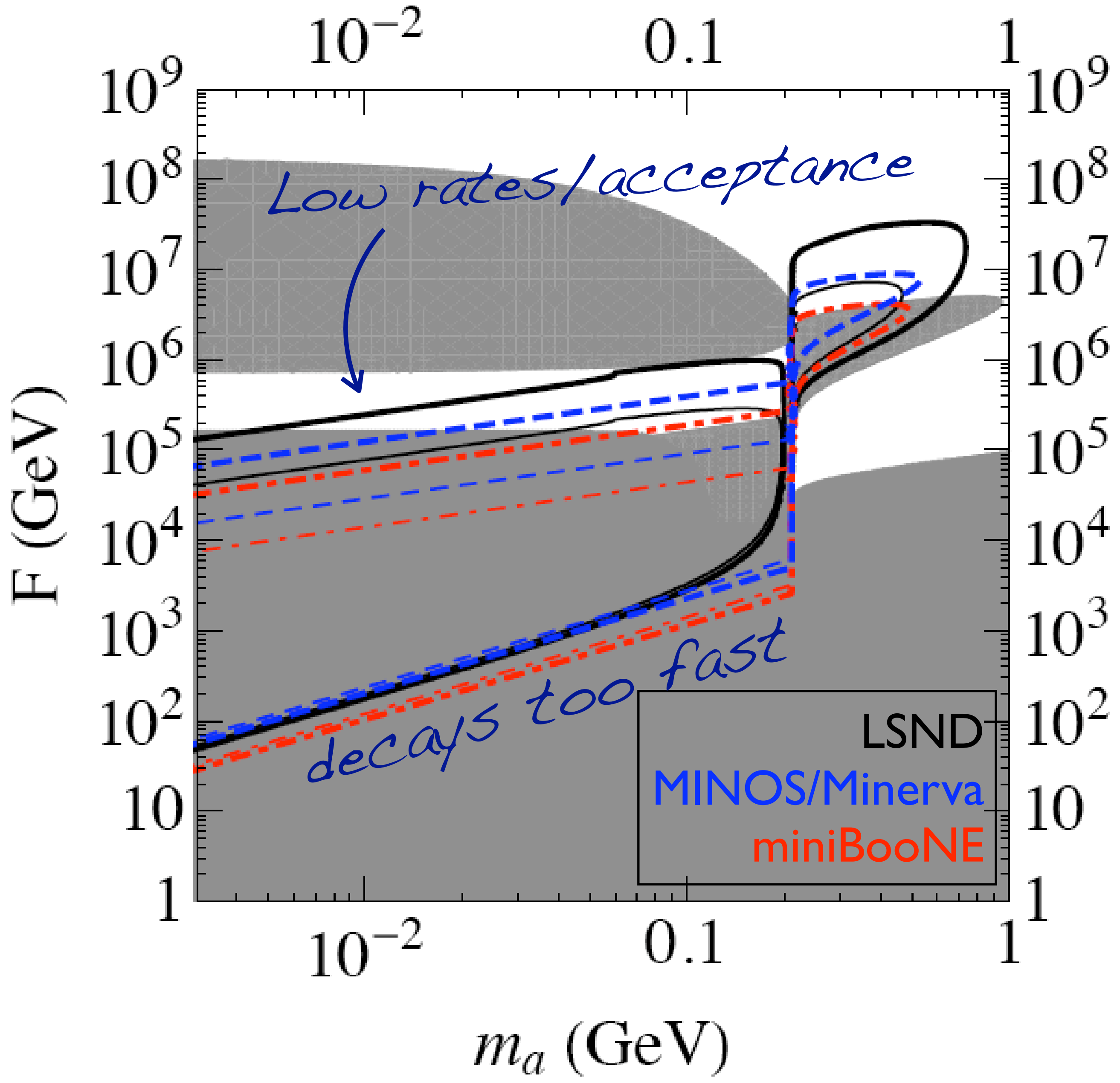
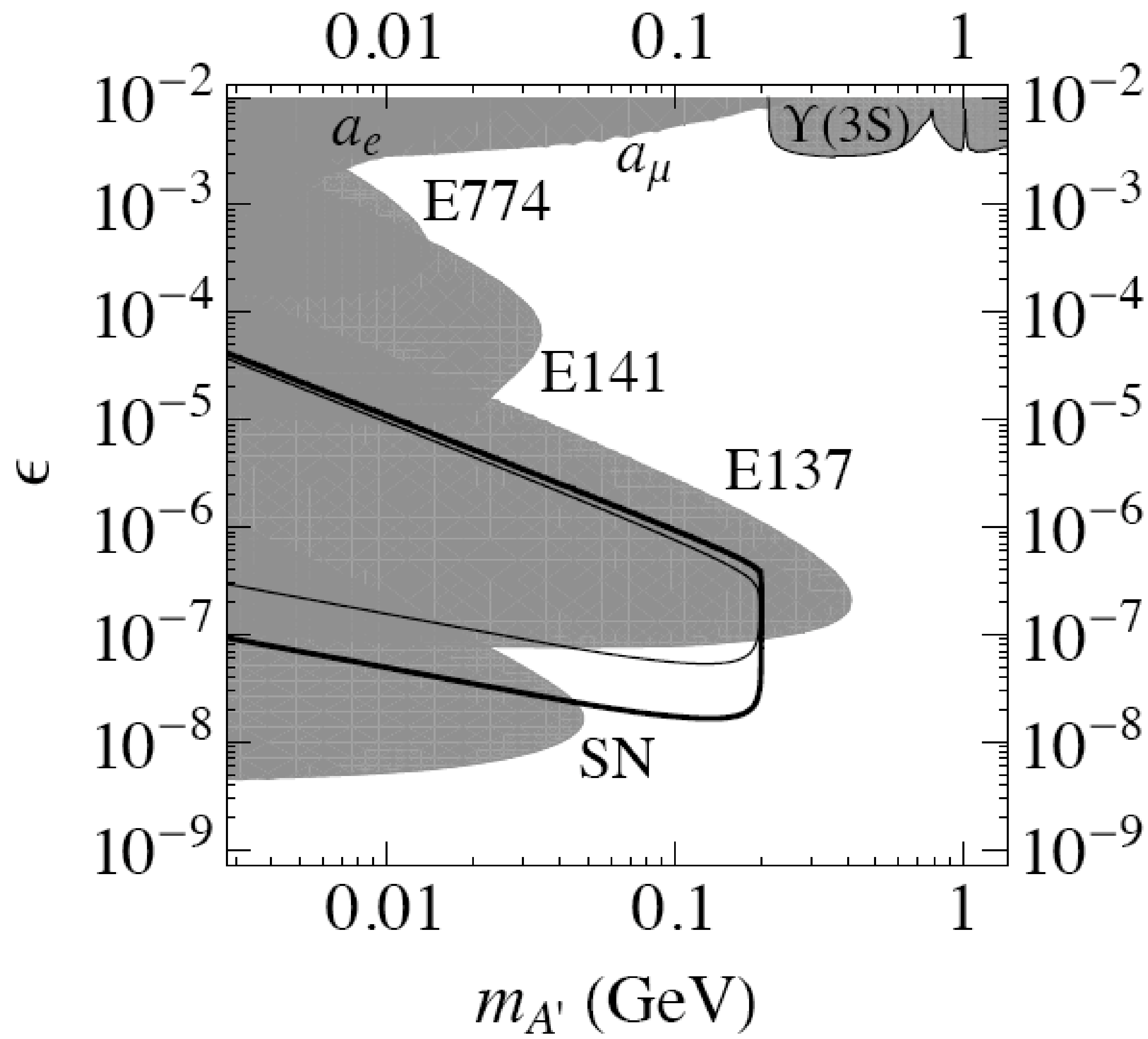


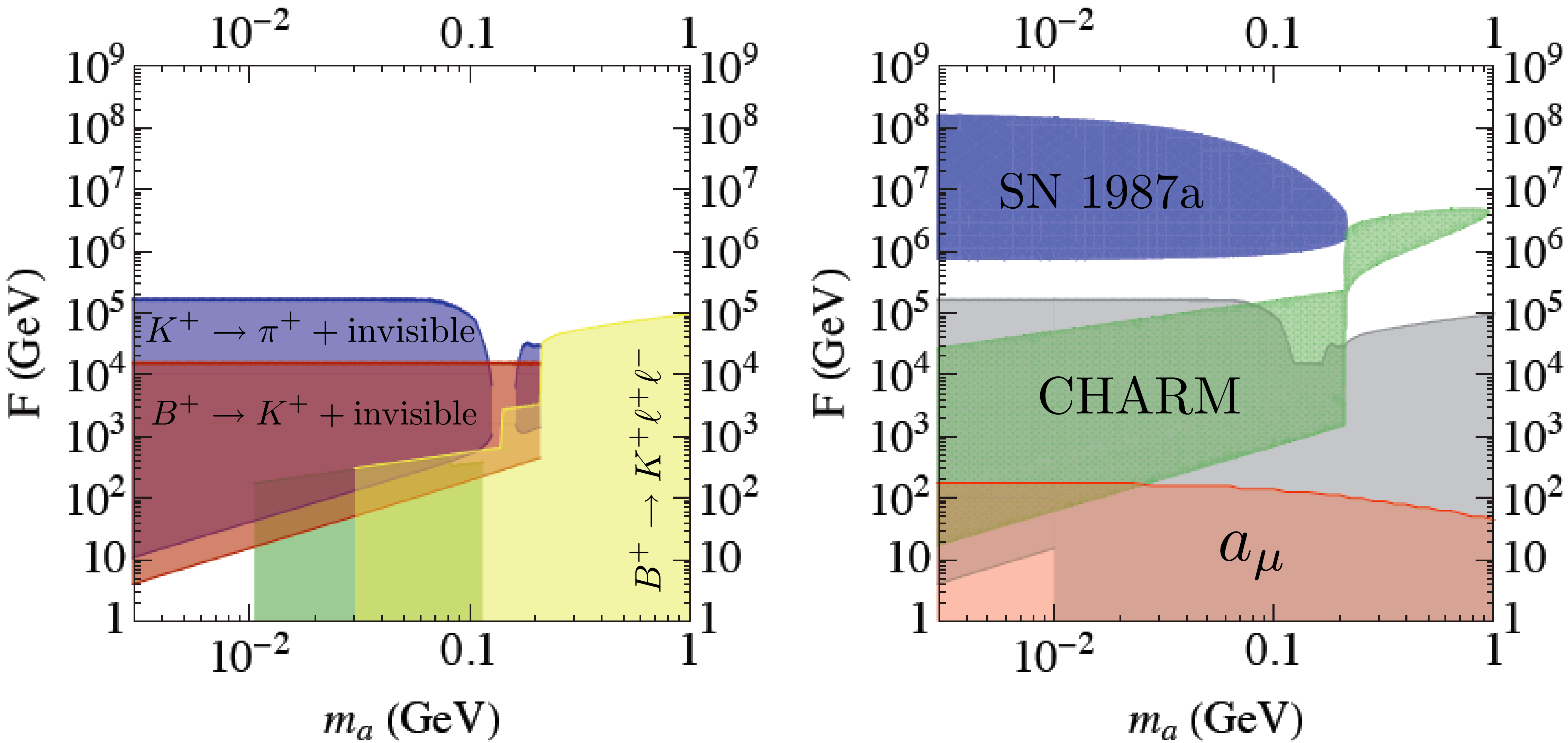
Dark Photon Limits

- Limits may be drawn in dark photon parameter space.
- Different production mechanisms (meson decays).
- LSND competes well.



Leptophilic Axion - Limits

- Axions could easily couple only to leptons. What are the limits then?



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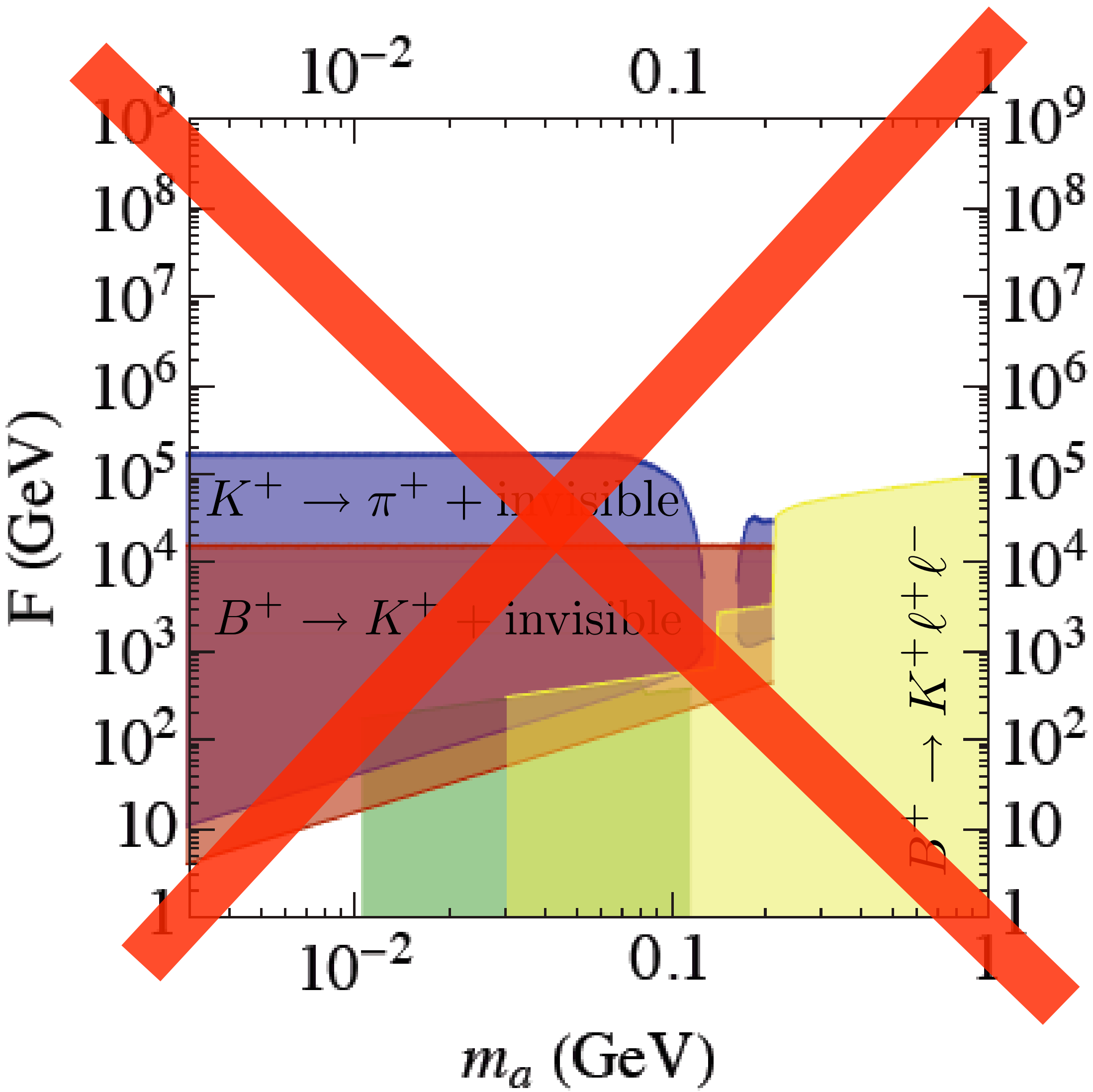

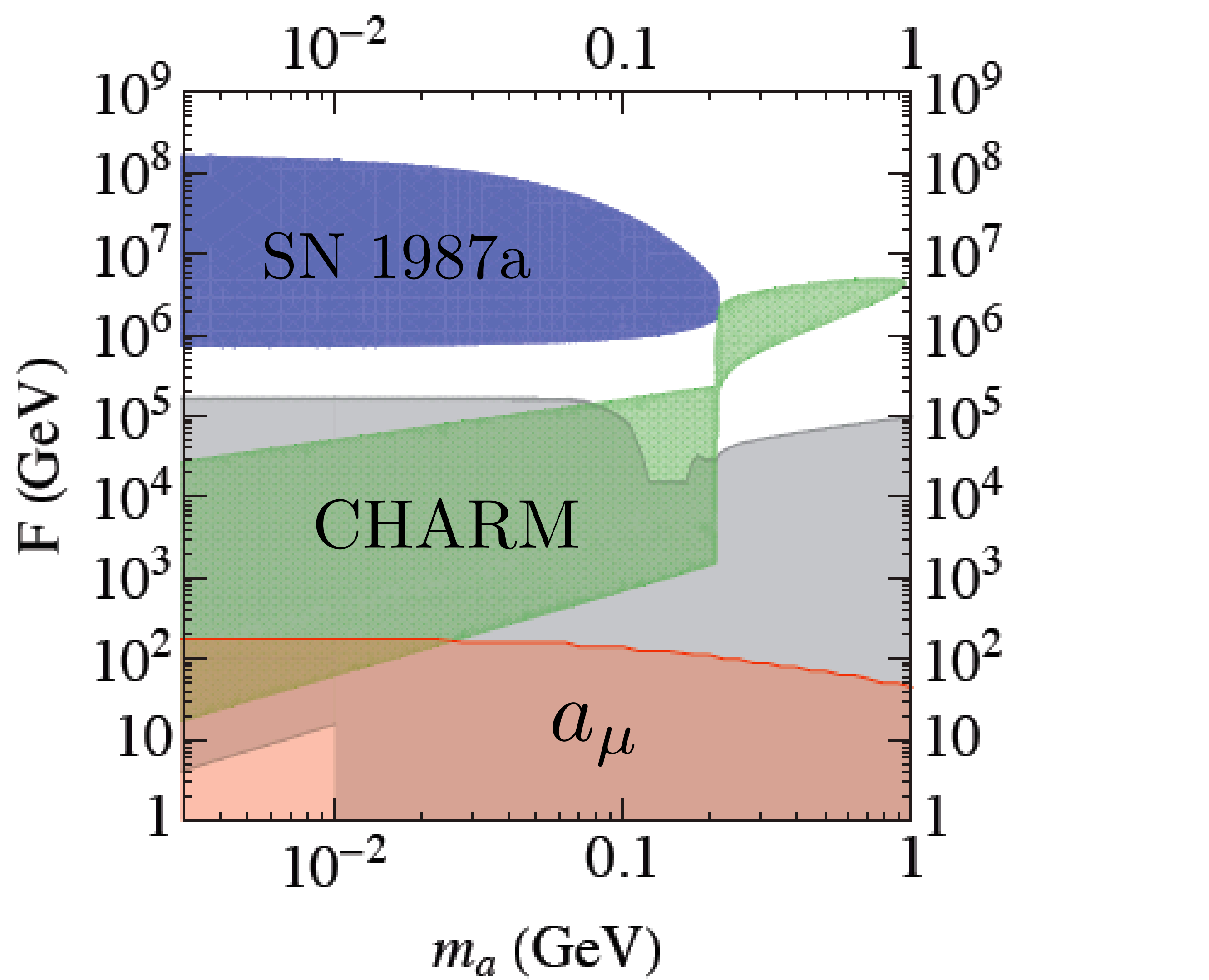

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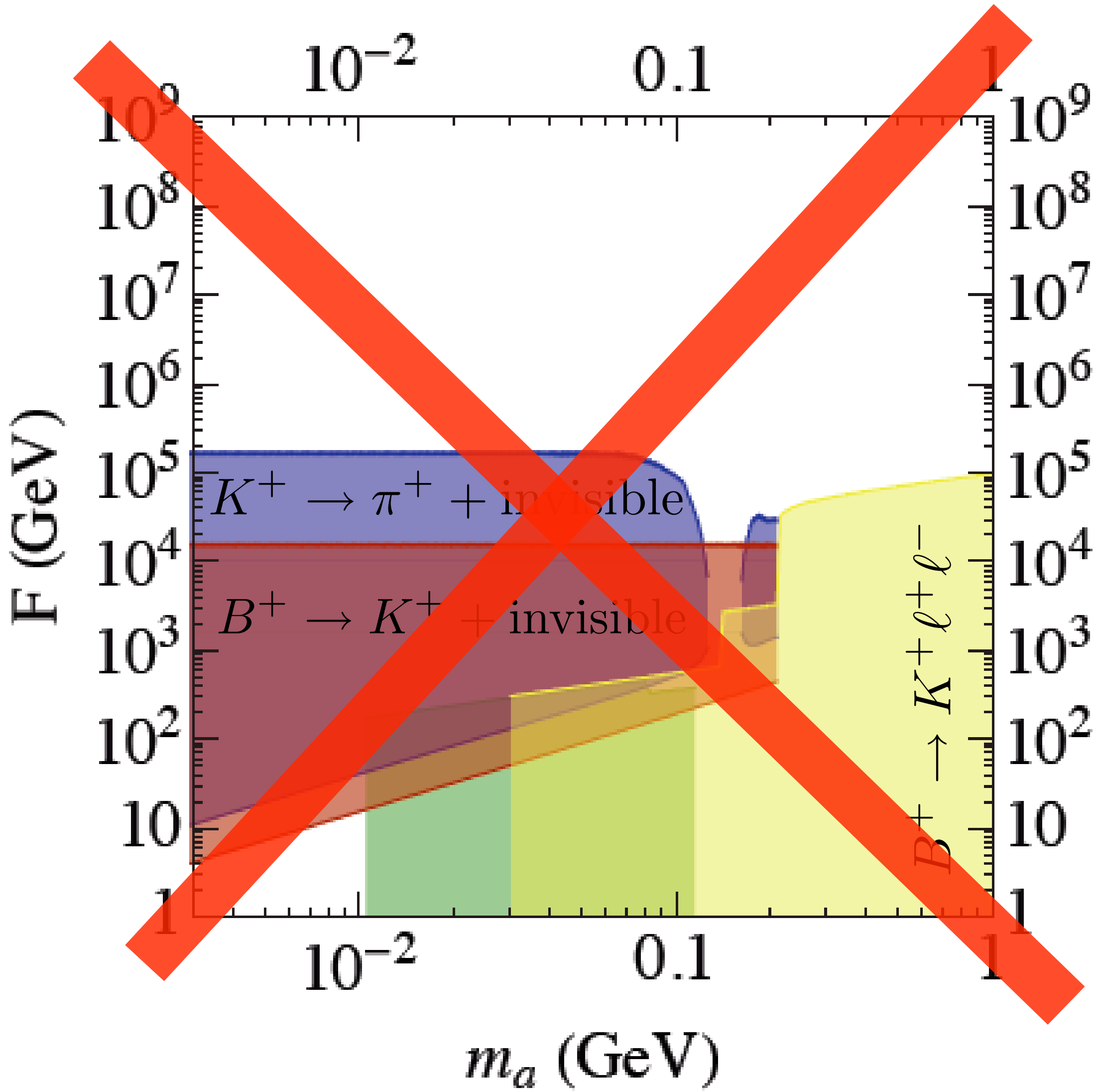

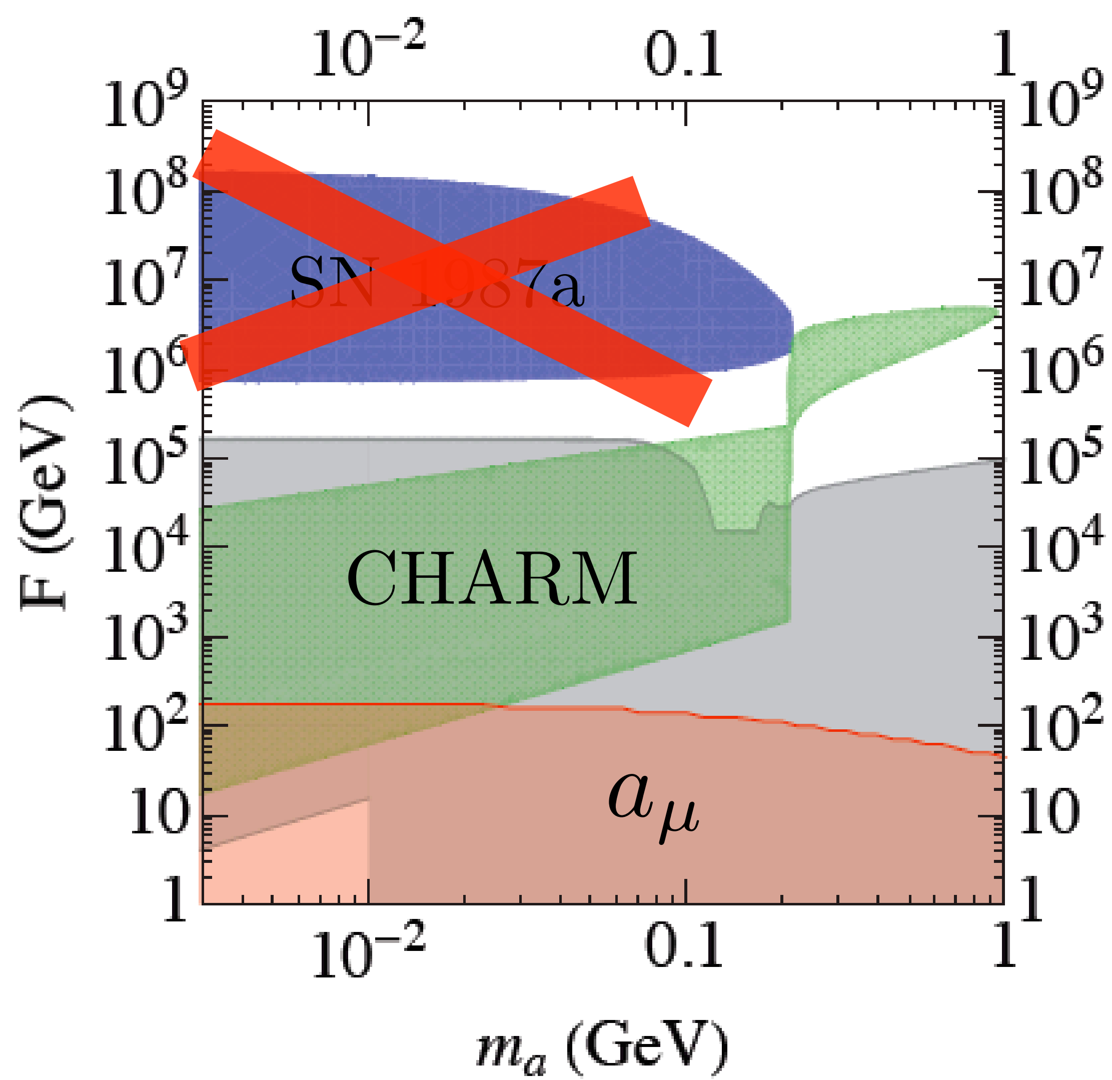

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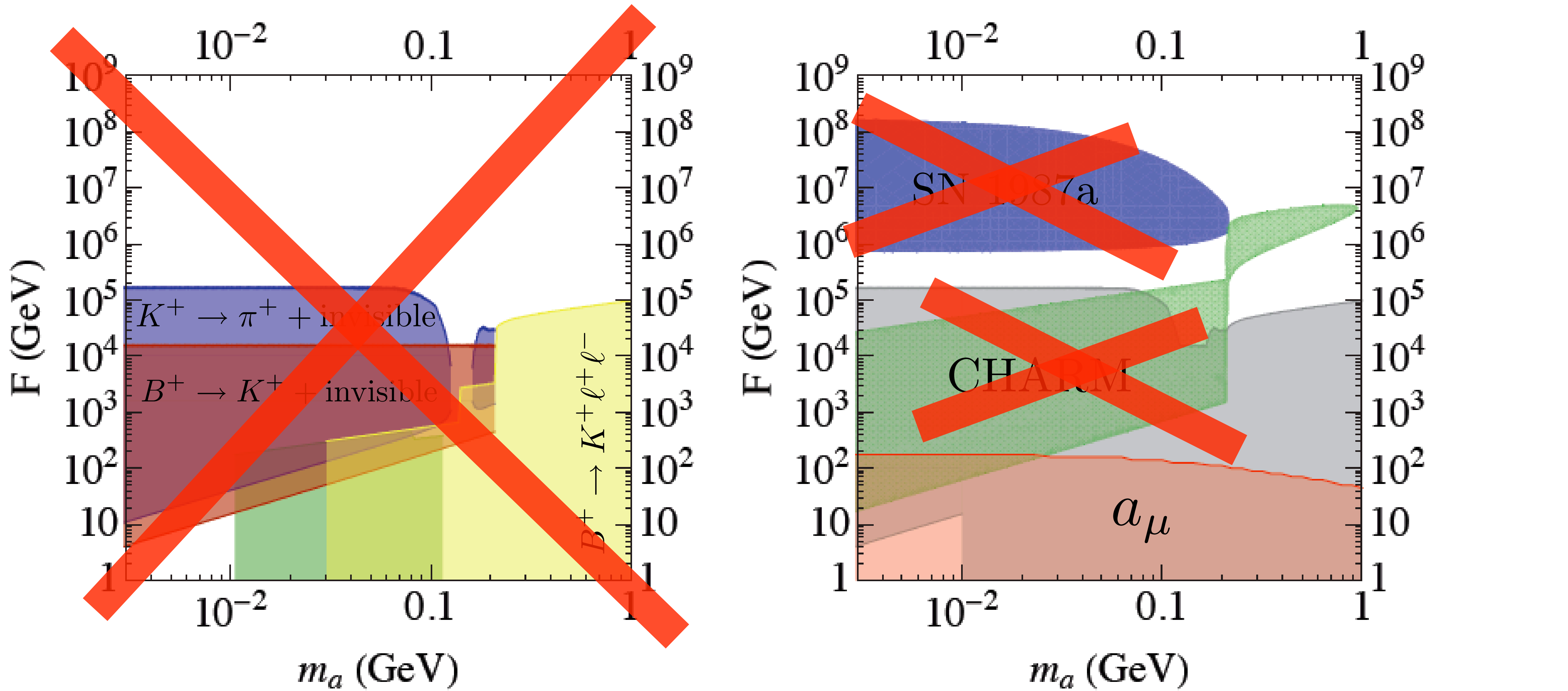

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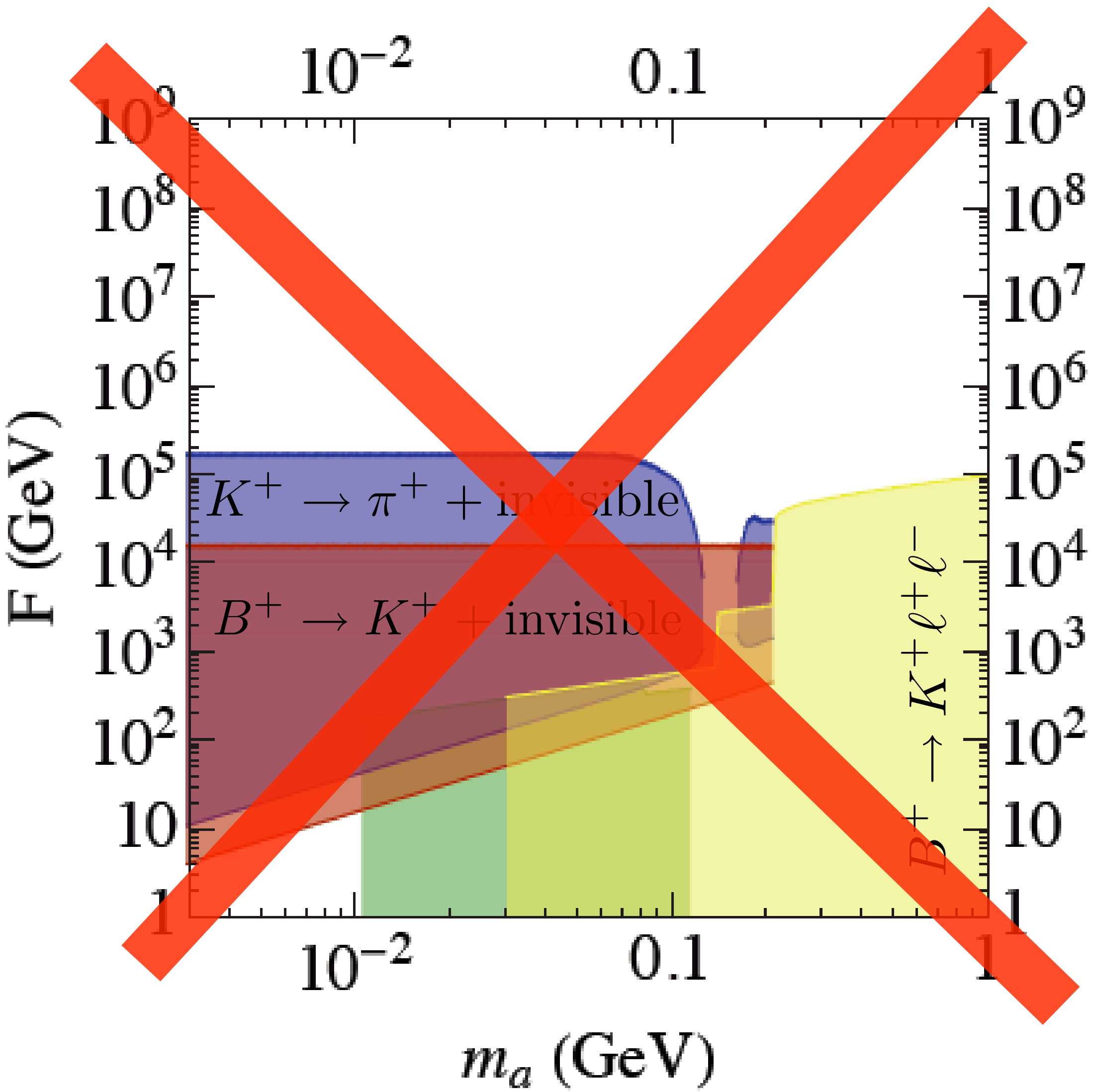
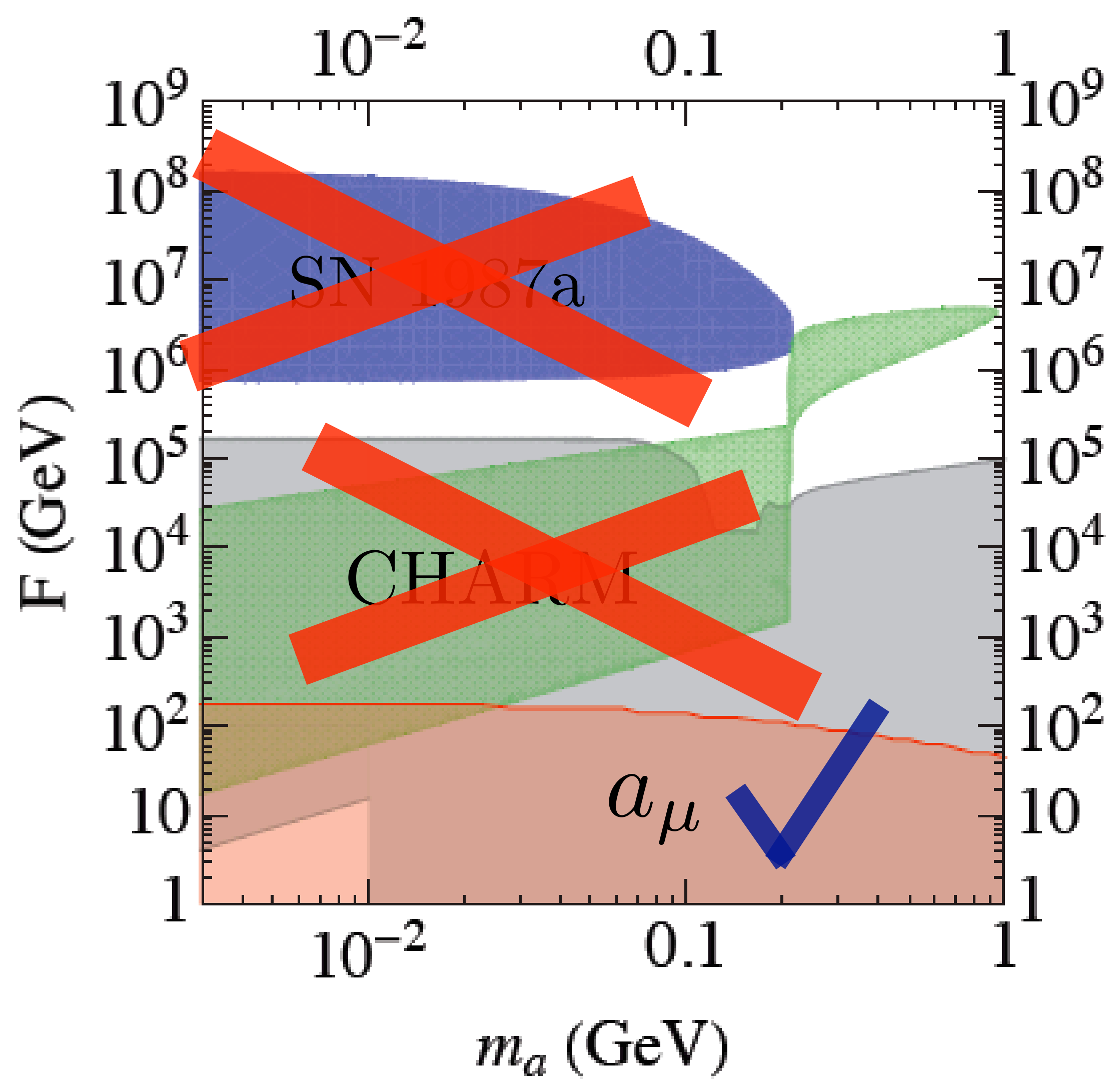
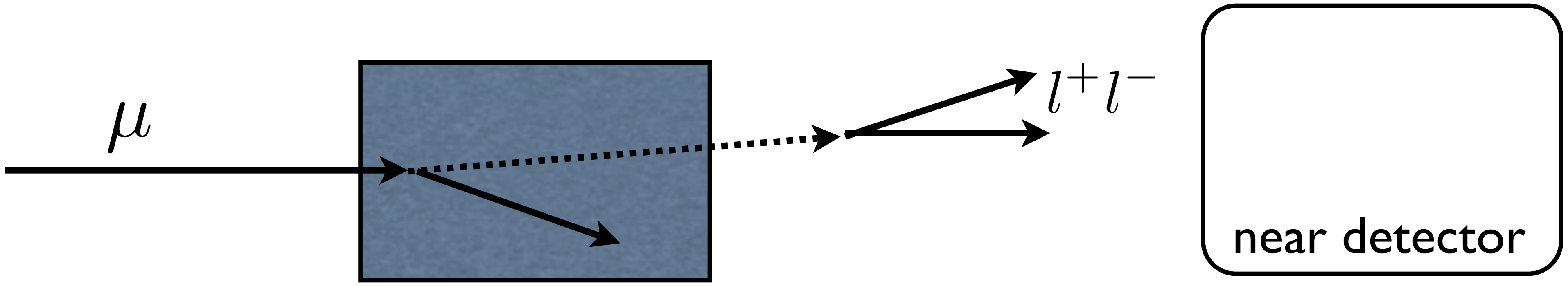




Muon Beam Dumps

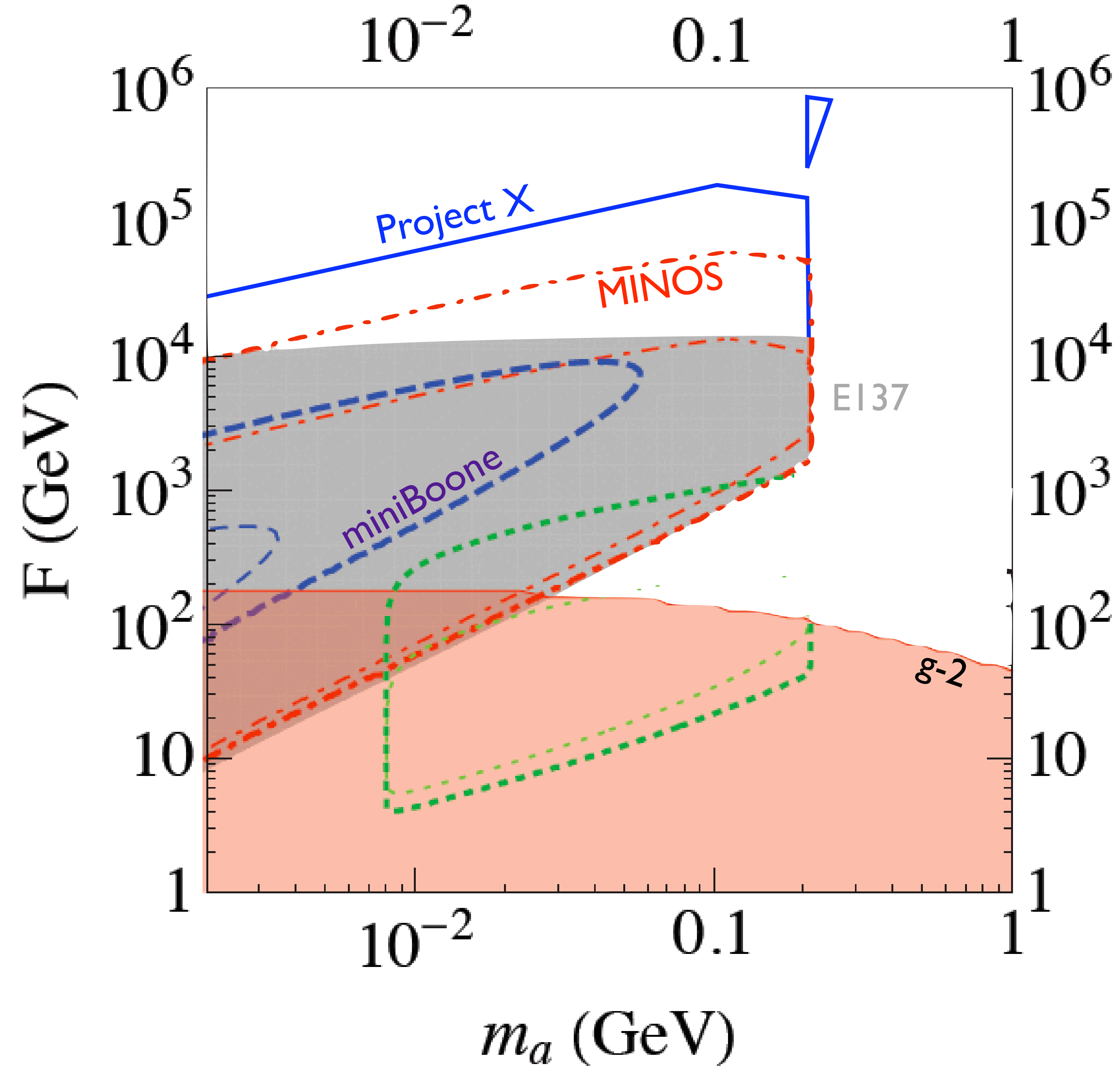
* Neutrino beams are also muon beam dumps.
* **NuMI is also the worlds most intense muon beam!**



* Muons have advantages:
  - Axion couple to mass.
  - Muon g-2 anomaly...?

Limits

* MIMOS/Minerva do well (compare to E137).
* Naive Project-X projection (N_{mu}=MINOS x 10) is obviously better!



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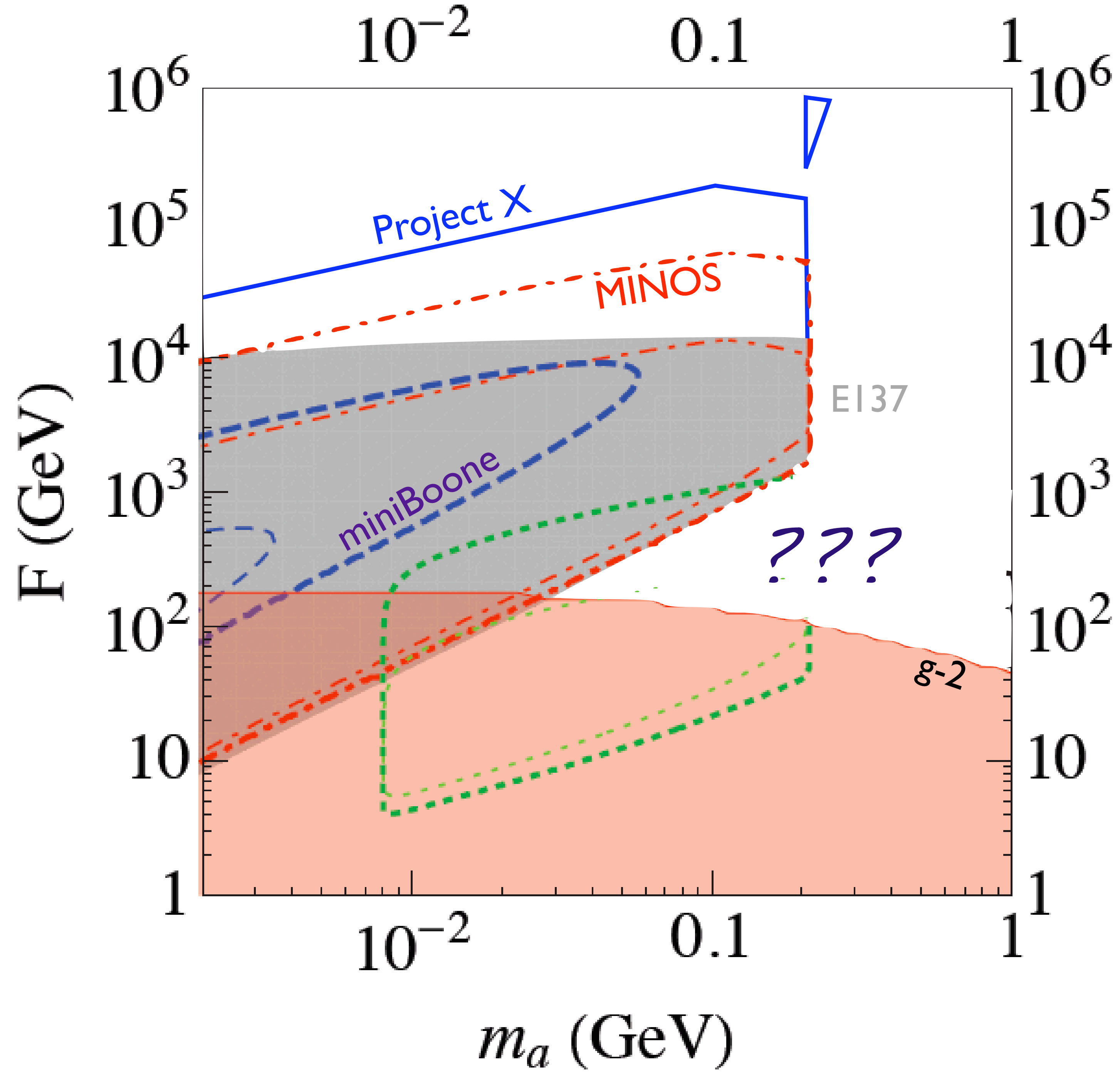
Need to get closer to the target...



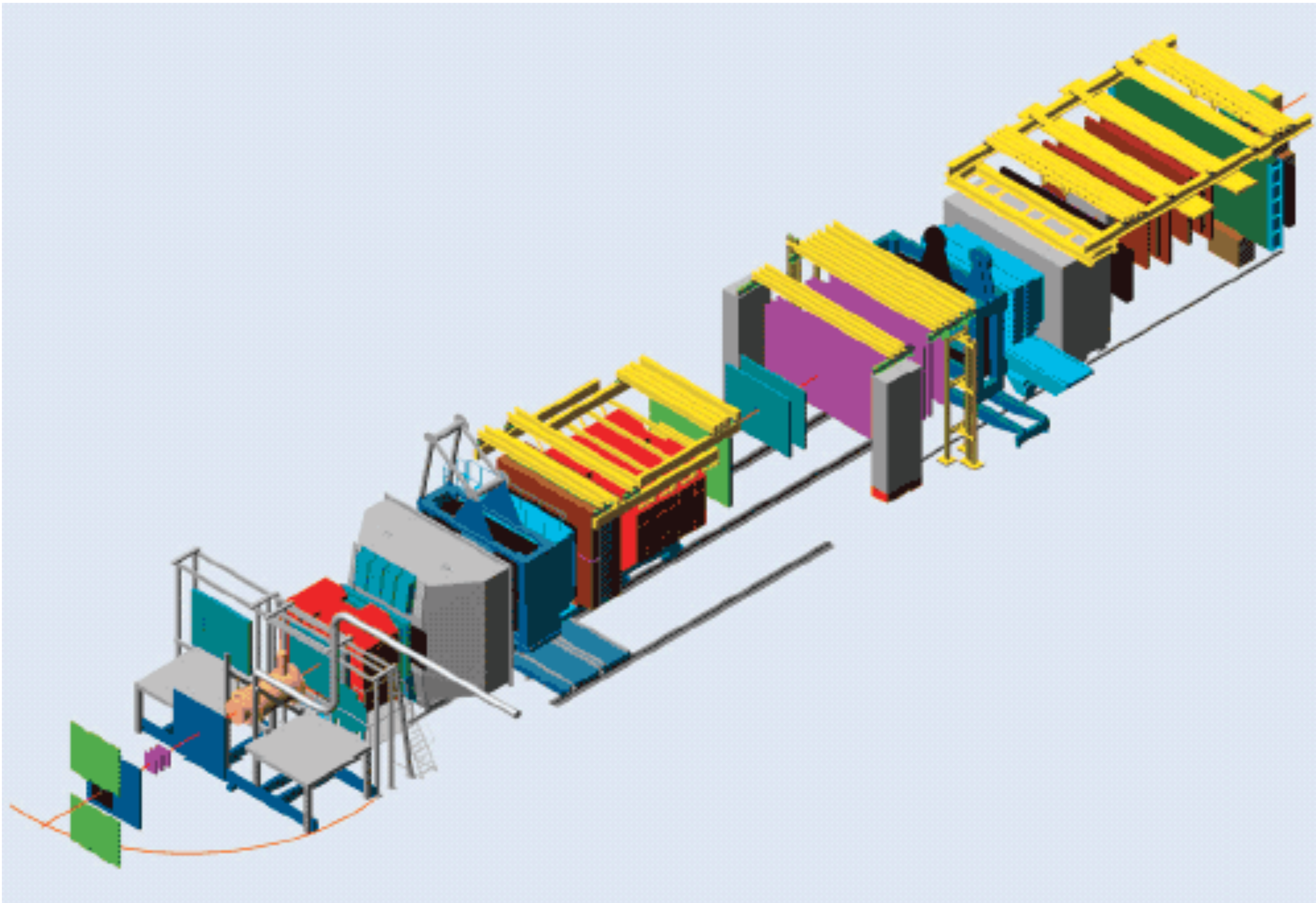
Muon Fixed-Target

Muon Fixed Target

* We have the world's most intense muon beam! What else can we do with it?
* It is tempting to consider fixed target setups (muons passing through a target with a very near detector).
* Muons have advantages:
  - Muons can pass through a thick target (several radiation lengths) without leaving a big mess!
  - Muon g-2.
  - Enhanced sensitivity to PNGBs.

COMPASS

* A muon fixed target experiment exists at CERN.

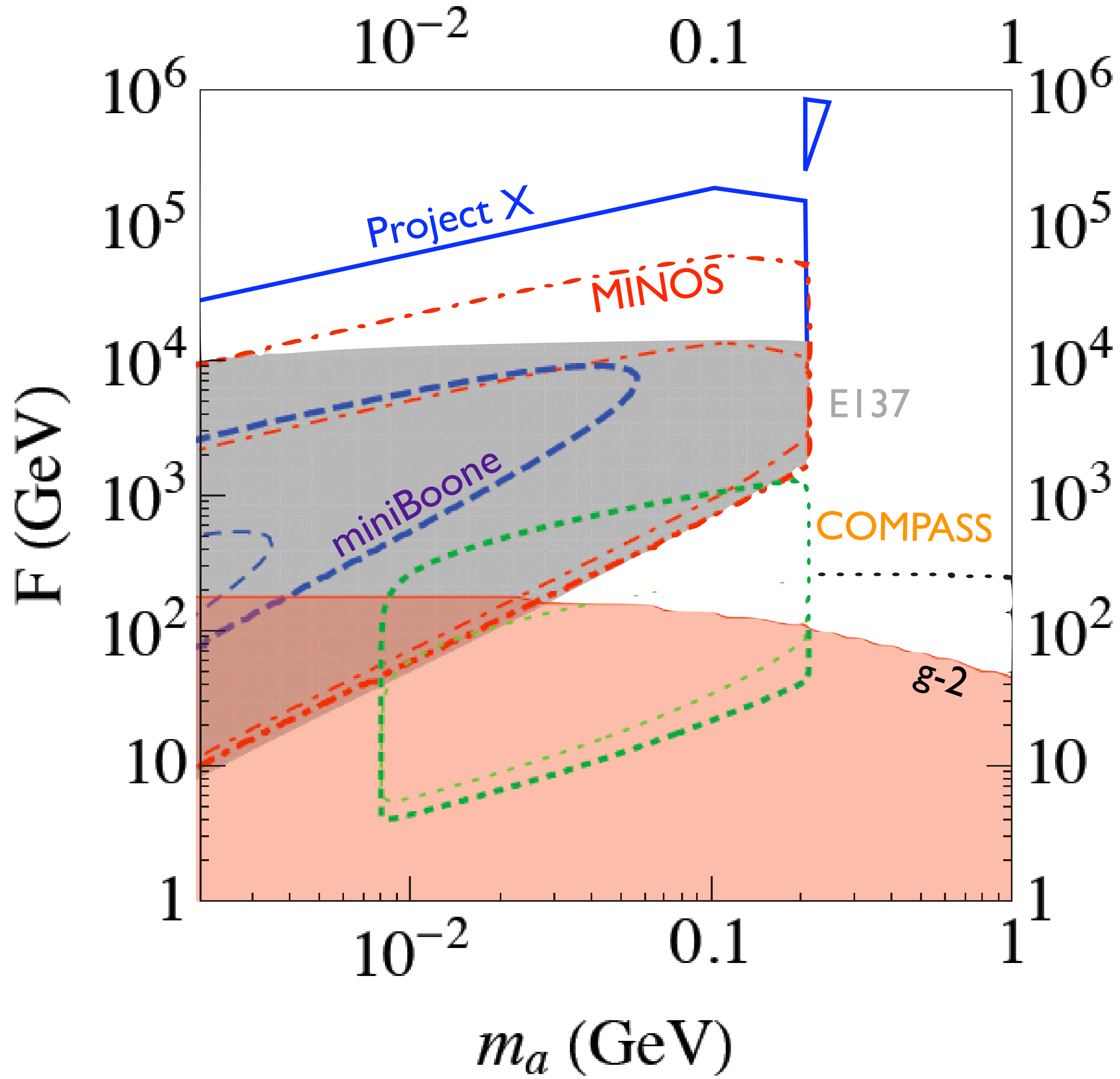


COMPASS

* A muon fixed target experiment exists at CERN.
* 160 GeV muon beam. Collected $\sim 10^{15}$ muons on a Lithium target (about 1.3 meters long).
* Two possible searches:
  - Displaced decay: look for a muon pair coming from a common point outside the target.
  - Bump hunt: look for an invariant mass peak over the SM continuum background.
* Can be improved with high-Z target.

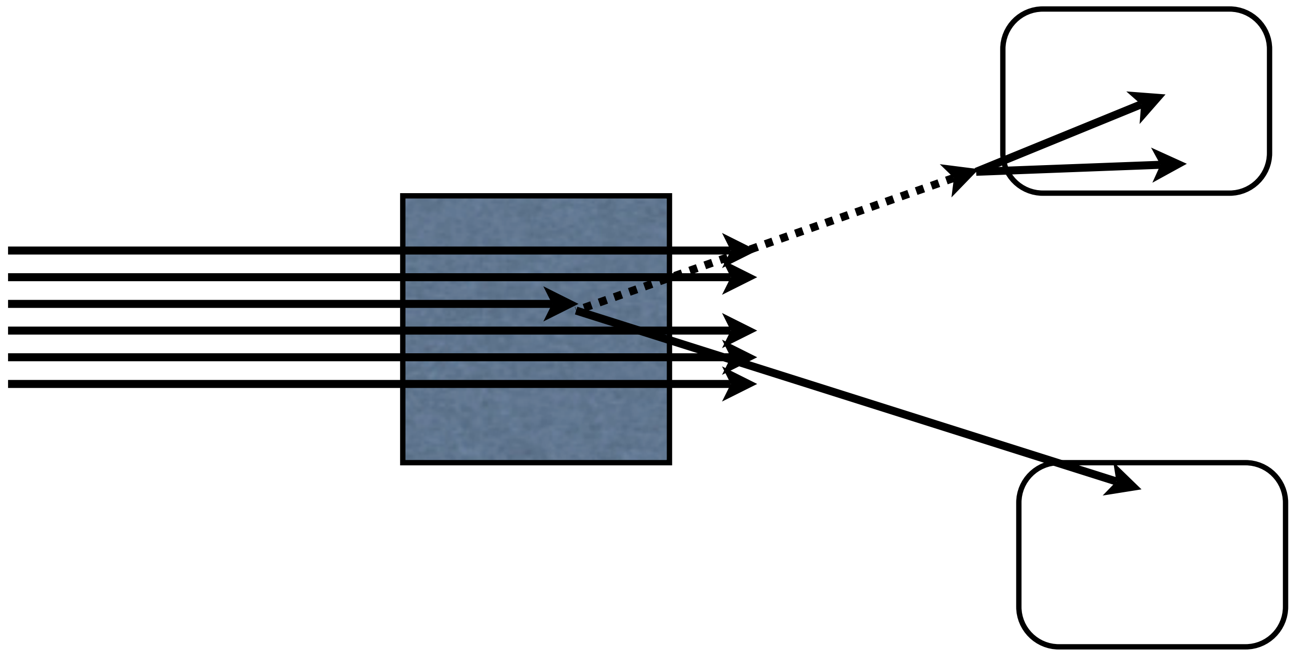
COMPASS

* COMPASS can cover interesting parameter space that's motivated by g-2.
* Further investigation needed for higher mass (form factor comes in).



Theorists can dream...

- Can we have a neutrino beam and a muon fixed target on the same beam-line?
- Can we focus NuMI muons before they hit the muon monitor?
- Could we instrument the Muon monitor area in NuMI to search for new particles?



$$\theta_a \lesssim \max\left(\frac{m_a}{E_0}, \frac{m_\mu}{E_0}\right)$$

Conclusion

* New particles can hide at **low mass** while having **feeble couplings**.
* Such NP may be probed at the **intensity** frontier.
* LSND places strong axion limits.
* MINOS/Minerva can get impressive limits on lepto-philic axions w/ **intense muon** "**beam**".
* COMPASS can cover regions interesting for g-2.
* Future facilities? Beam dumps? Muon Fixed target?

with existing data!

extras

“a-sstrahlung”

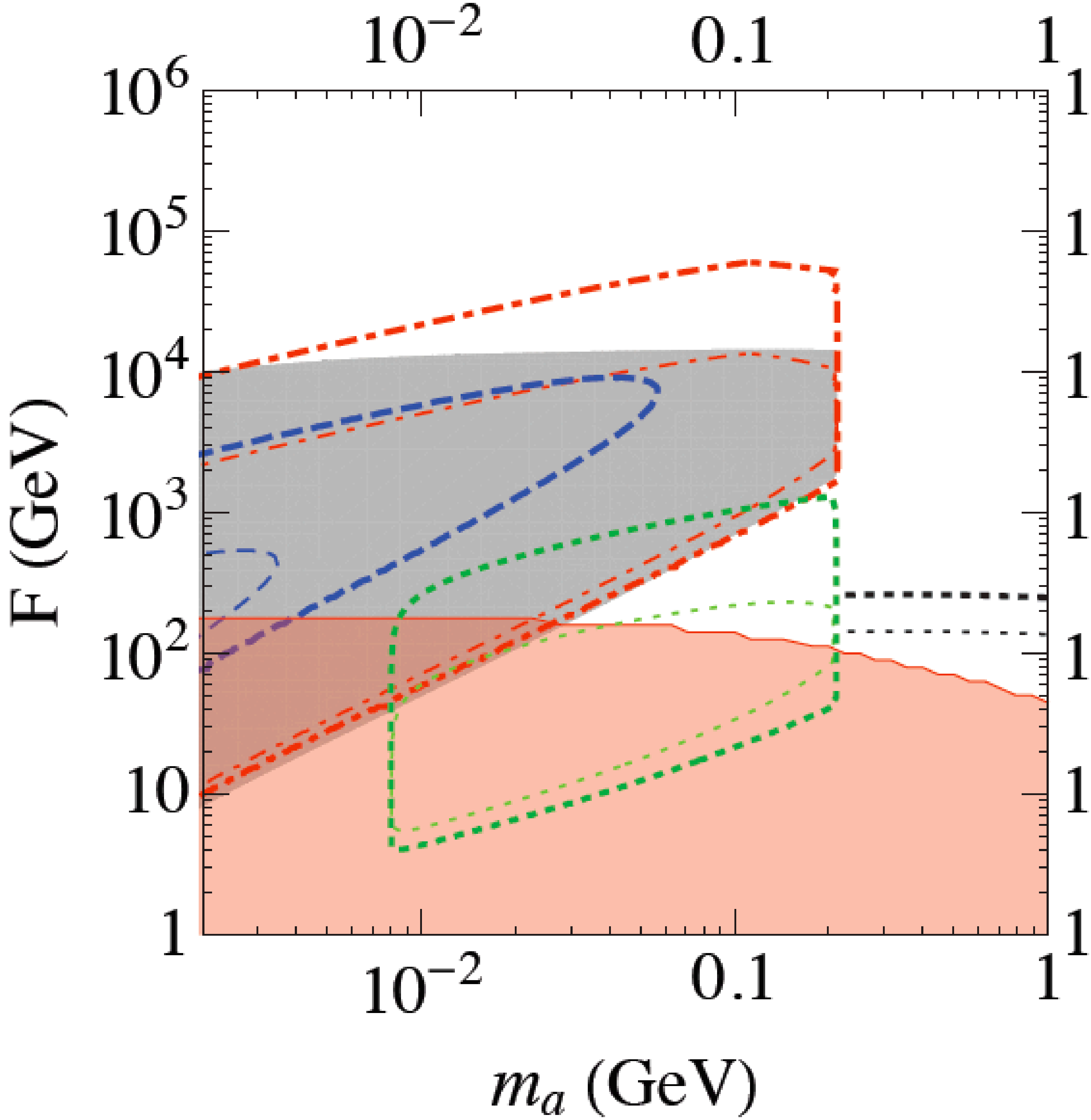
* Production cross section:

$$\sigma \approx \frac{m_\mu^2}{F^2}\frac{2\alpha^2}{\max(m_\mu^2, m_a^2)}$$

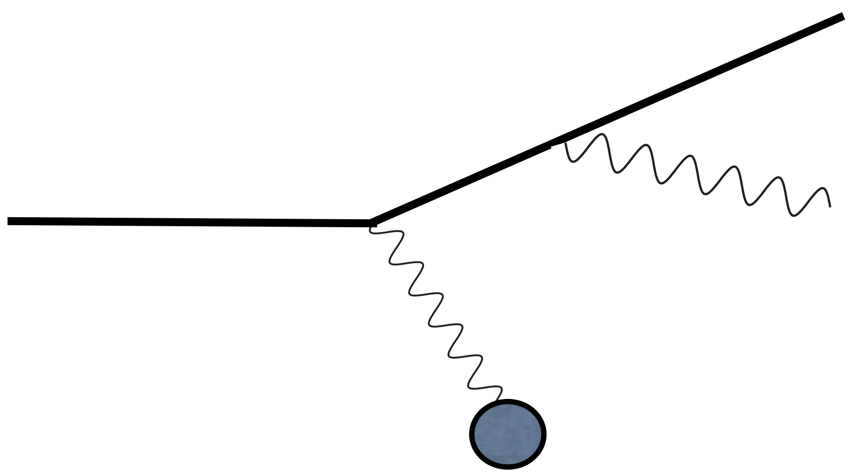
* Axion is typically produced forward with most of the beam energy:

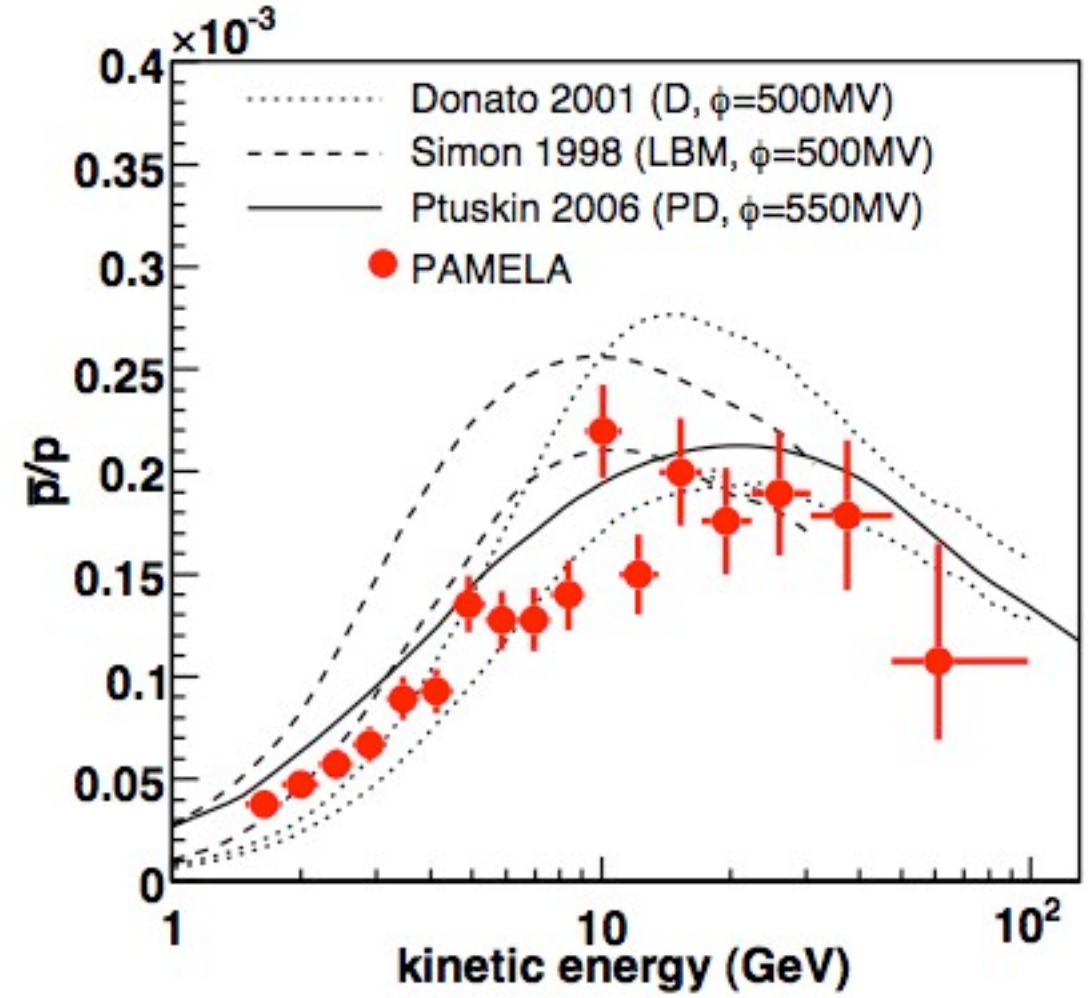
$$\theta_a \lesssim \max\left(\frac{m_a}{E_0}, \frac{m_\mu}{E_0}\right)$$

* For more details see: arXiv: 1008.0636



10^{-2}
0.1
1
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
F (GeV)
m_a (GeV)





$$\gamma c \tau \simeq \frac{3}{N_{\rm eff} m_{A'} \alpha \epsilon^2} \simeq \frac{0.8\mathrm{cm}}{N_{\rm eff}} \left(\frac{E_0}{10\mathrm{GeV}}\right) \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\,\mathrm{MeV}}{m_{A'}}\right)^2$$